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# MISSILE DEVELOPMENT TRADE STUDIES TO ACCOMPLISH LONG RANGE ENGAGEMENTS

Frank A. St. John and William M. Hester

Frank.Stjohn@lmco.com**(407) 356-7205**

William.M.Hester@lmco.com**(407) 356-4534**

Lockheed Martin Missiles and Fire Control – Orlando

## 1.0 Abstract

An emerging requirement for next generation tactical missiles is target engagements beyond the range of the missile sensor. These non-line-of-sight (NLOS) engagements present missile design challenges that require trade studies to insure that the missile performs within the constraints of the total weapon system. NLOS performance is a function of missile kinematic range, missile navigation performance, targeting sensor, missile sensor, communication infrastructure and engagement geometry. The Longbow 6-DOF simulation was modified for Monte Carlo analysis of NLOS engagements. Analyses were conducted in the following trade space: Engagement Scenarios including autonomous and remote targeting; engagement timeline from 2-30 second handover delay; target kinematics such as fixed, stationary, and moving; spotter, shooter, target geometry; missile IMU quality; spotter, shooter GPS quality; varied targeting sensors; target range; and missile acquisition sensor range. Conclusions from the trade study include:

- Performance under all conditions is driven by the following:
    - Initial targeting errors
    - Engagement timeline
    - Missile sensor acquisition range and search rate
- Cooperative engagement performance is a function of engagement geometry.
- The requirement to engage moving targets at very long ranges without an in-flight target update to the missile can only be met with a long-range missile sensor.

## 2.0 Introduction

Recent and current tactical missile program activities have generated sets of missile performance requirements that present multiple design challenges. Included in these requirements are limited missile diameter and length, reduced weight, increased range, increased lethality, interface to multiple platforms (legacy and future), and reduced cost.

Perhaps the most challenging requirement is mission flexibility. A next generation tactical missile will no doubt replace many missiles (TOW, Hellfire, Longbow, Maverick) currently in service and will be required to perform in widely varied mission scenarios. Engagements may be either precision or fire-and–forget (F&F). Missile sensor acquisition may be either lock-on-before-launch (LOBL) or lock-on-after-launch (LOAL). Targeting data will either be generated on the shooter platform or transmitted to the shooter via a communication network. Targets will be fixed, stationary, and moving and will include not only armored vehicles but also wheeled vehicles, ships, bunkers, and buildings. Finally, a next generation tactical missile will be required to perform missions under nominal conditions, adverse weather, and in countermeasures environments.

Precision engagements result in a very accurate terminal guidance solution. Historically these missions have been accomplished with an operator "in the loop" either steering the missile from the launch platform (command-line-of-sight) or with a laser designator. The high degree of accuracy has great utility in close combat situations, limits collateral damage, and provides performance against a wide variety of targets. Laser designation of targets is robust and flexible and often the targeting is performed

by an asset other than the shooter platform. However, precision engagements, even those performed cooperatively are a survivability risk as an operator must have "eyes on target" for some portion of the missile flight.

A second and often preferred method of engagement is fire-and-forget. Advances in sensor and processor technology now allow many engagements to have no operator intervention after trigger pull. In many cases a target is acquired by the missile sensor prior to launch (LOBL) and tracked to impact. Targets are passed from a launch platform to the missile using video correlation, operator cues (cross-hair or track box) in video, or with a digital message containing pointing commands or inertial coordinates. The range at which targets can be engaged using LOBL is typically limited by the ability of the missile sensor to acquire and track a selected target. Alternatively, the missile can acquire targets after launch (LOAL). These missions typically involve a known set of targets (military vehicles) and require that the missile navigate toward an anticipated target position until the missile sensor can acquire. LOAL also known as non-line-of-sight (NLOS) enables tactical missiles to strike targets at ranges that far exceed the acquisition range of the missile sensor. LOAL performance is a function of missile kinematic range, missile navigation performance, targeting sensor, missile sensor, communication infrastructure and engagement geometry.

For any mission, the relationships between and performance of the targeting system, launch platform, and missile system are critical. A design approach that includes every element of the weapon system is required for a next generation missile design. This is especially critical for LOAL engagements. This paper presents analyses that examine the relationship between these weapon system characteristics. Data is presented for LOAL engagements against fixed and moving targets using targeting information generated both on and off of the shooter platform.

## 3.0 LOAL Engagements

LOAL targeting is preferred in many operational scenarios such as:

- When the target is beyond the LOBL range of the missile seeker.
- When the target is within the LOBL range of the missile seeker, but the threat environment prohibits exposing the shooter platform to achieve LOS prior to launch.
- When the environment is target rich, and rules of engagement do not require target confirmation prior to launch.

LOAL targeting is generally more difficult than LOBL targeting. Figure 3.0-1 illustrates an optimal LOAL engagement where there are no weapon system errors at work. Using pre-launch targeting data the missile inertially tracks the target during fly-out until it reaches its seeker's acquisition range. At this point, the seeker acquires the target (ideally located within its field of view) using an automatic target acquisition (ATA) function and terminal guidance commences.
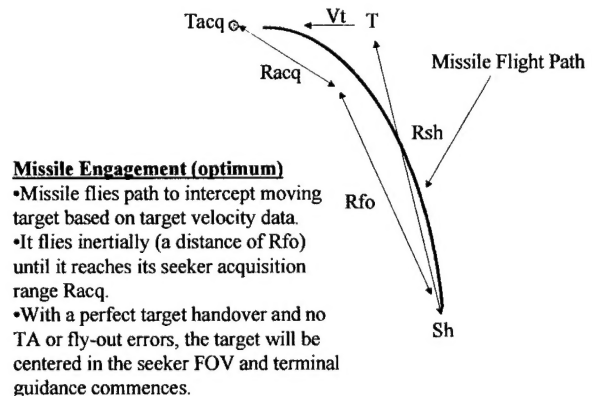


**Missile Engagement (optimum)**
•Missile flies path to intercept moving target based on target velocity data.
•It flies inertially (a distance of Rfo) until it reaches its seeker acquisition range Racq.
•With a perfect target handover and no TA or fly-out errors, the target will be centered in the seeker FOV and terminal guidance commences.

**Figure 3.0-1 Optimal LOAL Engagement.**

There are, however, several weapon system error sources that combine to make the autonomous LOAL engagement a more difficult problem. These errors include:
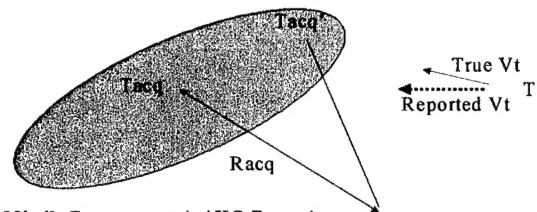
- Target position and velocity errors as reported by the targeting sensor.
- Inertial alignment errors between the missile and the launch platform.
- Missile inertial fly-out errors.
- Target acceleration.

Many of these errors grow over time, so the delays in transferring targeting data to the missile and the length of time the missile must fly inertially prior to acquisition (fly-out range) are critical.

Position and velocity errors from the targeting sensors vary depending on the type of sensor (EO, RF, Scanning, Staring), the sensor line of sight stability, and the algorithm set used to generate targeting data. For example, an RF sensor can provide very accurate measurements of radial target velocity, but its estimates of angular position and cross range rate are less accurate than those taken by an EO sensor. Transfer alignment between the sensor, the platform INS, and the missile INS is also critical and must me minimized for optimal LOAL performance These errors arise primarily due to the large number of mechanical interfaces between the sensor and the missile INS and result in a skew of the missiles inertial frame of reference (position, attitude and velocity) relative to the frame of reference of the sensor. On modern platforms with digital missile interfaces, these errors are minimized by passing platform inertial data to the missile and dynamically resolving the coordinate frame misalignment. On legacy platforms with more rudimentary missile interfaces this problem is more severe. Once launched the missile navigates to an anticipated target intercept point. This requires a knowledge of the missile's location that drifts during fly out due to errors within the missile INS. Lastly, in the case of moving targets, there is always opportunity for the target to change direction or velocity during missile fly-out.

The cumulative effect of these errors is an uncertainty in the target's true position at the time when the missile reaches acquisition range. Thus the missile sensor must search an "error basket" to find the target. In some cases this area is smaller than the missile sensor's field of view and the missile can rapidly acquire. In other cases the error basket is quite large and stresses the sensor's ability to locate and detect the target. This is illustrated in the Figure 3.0-2.
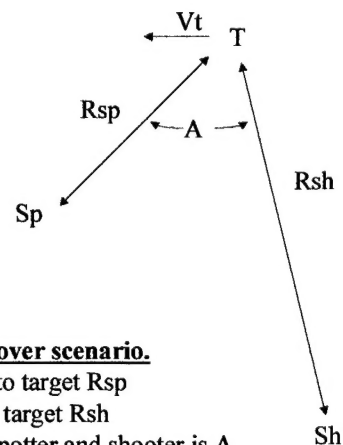


**Missile Engagement (w/ HO Errors)**
•The target is not located at Tacq due errors in the targets position and velocity handover.
•The positional errors are a fixed bias.
•The velocity errors grow with the time between detection and seeker acquisition.
•The seeker must search a large FOR to find the target at Tacq'.

**Figure 3.0-2 LOAL Engagement With Weapon System Errors.**

To engage targets exceeding the range of the shooting platform's onboard sensors, cooperative LOAL targeting must be employed, and the constraints become even more demanding. This scenario is illustrated in Figure 3.0-3 below.



**Remote target handover scenario.**
•Spotter is has range to target Rsp
•Shooter has range to target Rsh
•The angle between spotter and shooter is A
•The target has velocity Vt

**Figure 3.0-3 Cooperative LOAL Engagement**

Added to the error sources mentioned above for autonomous engagements are the following:
- Spotter position and heading errors
- Shooter position and heading errors
- Additional data transfer latency

Position and heading errors on the spotter and shooter platform result in additional coordinate frame misalignment when targeting data is passed from the spotter to the shooter. Communicating this targeting data to the

shooter adds additional steps to the mission timeline. Furthermore the extended range of the engagement includes a longer fly-out time. The weapon system error characteristics vary depending on the engagement scenario dividing LOAL targeting into four major categories. The divisions are drawn between autonomous or remote targeting sensors, and fixed or moving targets. Figure 3.0-4 highlights the issues involved with each.

| Autonomous Detection | Fixed Target | Engagements limited by targeting sensor 5-8km Seeker search volume drivers: •Targeting sensor positional errors •IMU alignment/flyout errors |
| Remote Detection | Fixed Target | Engagements limited by missile range 12-18km Seeker search volume drivers: •Targeting sensor positional errors •Sensor to Shooter transformation errors •IMU alignment/flyout errors |
| Autonomous Detection | Non-Fixed Target | Engagements limited by targeting sensor 5-8km seeker search capability Seeker search volume drivers: •Targeting sensor velocity errors •Detection to seeker acquisition latency •Target acceleration |
| Remote Detection | Non-Fixed Target | Engagements limited by seeker search capability Seeker search volume drivers: •Targeting sensor velocity errors •Sensor to Shooter geometry •Detection to seeker acquisition latency •Target acceleration |

**Figure 3.0-4 LOAL Targeting Scenarios and Associated Performance Drivers.**

## 4.0 Study Methodology

The Longbow weapon system currently performs LOAL engagements. The missile is inertially aligned to the platform and targets are passed to the missile via digital data transfers. These characteristics make the validated Longbow 6-DOF a useful tool for performing LOAL trade study analysis. The initial study involved autonomous engagements. Changes to the baseline simulation included:
- Motor thrust changes to allow for extended range.
- Trajectory changes driven by range extensions.
- Modifications to models of legacy and future targeting sensors.

The resulting simulation was used in a trade study that varied the following parameters:
- Targets (Fixed and Moving)
- Targeting Sensor Type (RF, EO)
- Target Engagement Range

- Missile Sensor Acquisition Range

Sets of 100 Monte Carlo runs were performed with missile sensor pointing error statistics collected at the point when the missile reached acquisition range.

The simulation was then further modified to add a spotter platform that enabled cooperative LOAL engagements. The resulting simulation was used in a trade study that varied the following parameters:
- Targets (Fixed and Moving)
- Target velocity vector angle to shooter (0 and 90 degrees)
- Targeting Sensor Type (RF, Improved RF, EO, Improved EO)
- Geometry between spotter and shooter relative to target (0,20,45,85 degrees)
- Targeting Data Latency (0,5,10,30 seconds)
- Target Engagement Range (12, 15, 18 kilometers)
- Missile Sensor Acquisition Range (3,5,7 kilometers)
- Spotter range to target (5 or 10 kilometers)
- Spotter/Shooter heading accuracy (standard and improved)
- Spotter/Shooter GPS accuracy (standard and improved)
- Missile IMU quality (1deg/hr and 10deg/hr gyro drift rates)

Again, sets of 100 Monte Carlo runs were performed with missile sensor pointing error statistics collected at the point when the missile reached acquisition range.

## 5.0 Study Results

### 5.1 Inertial Navigation Performance

The effect of transfer alignment errors and IMU quality on target pointing errors was determined by zeroing targeting data errors in the simulation. The effectively creates a perfect LOAL target handover. Range and pointing angle errors as a function of launch range and missile sensor acquisition range are shown in the Figures 5.1-1 and 5.1-2, respectively.
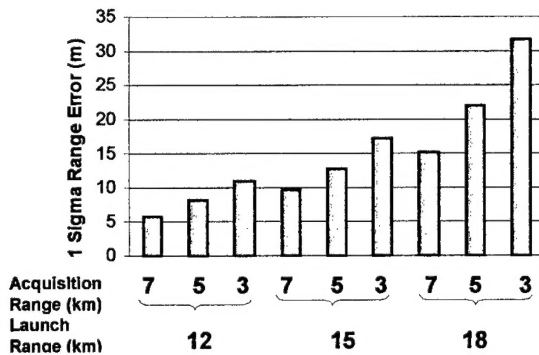
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**Figure 5.1-1 Range Uncertainty Caused by Missile Inertial Errors.**
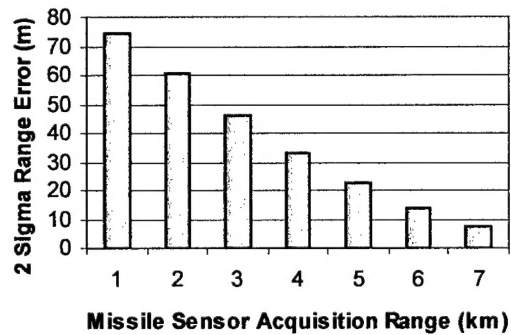


**Figure 5.2-1 8k Stationary Target Range Error versus Seeker Acquisition Range RF Handover.**
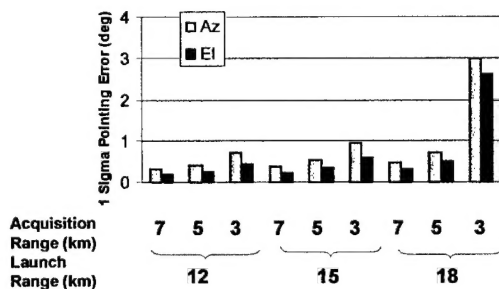


**Figure 5.1-2 Pointing Uncertainty Caused by Missile Inertial Errors.**
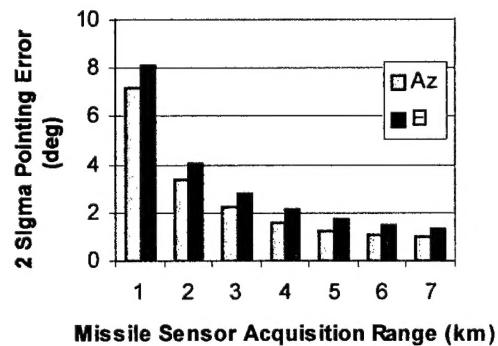


**Figure 5.2-2 8k Stationary Target Pointing Errors versus Seeker Acquisition Range RF Handover.**

Even for extended fly-out ranges up to 15km, the inertial navigation errors caused by the missile IMU are minimal. Subsequent studies performed under contract modeled multiple IMUs with varied performance. Little effect on the performance of the missile was observed confirming the data above. This is consistent with the fact that missile flight times to these ranges are small when compared to IMU drift rates.

## 5.2 Autonomous Engagement Study

For fixed targets, the graphs presented in Figures 5.2-1 through 5.2-4 below are the 2-sigma range, azimuth, and elevation errors for 8-kilometer engagements using first an RF sensor for acquisition and then an EO sensor for acquisition. Range errors are presented as a consideration for RF missile sensors that are range gate limited in their ability to detect and subsequently track targets.
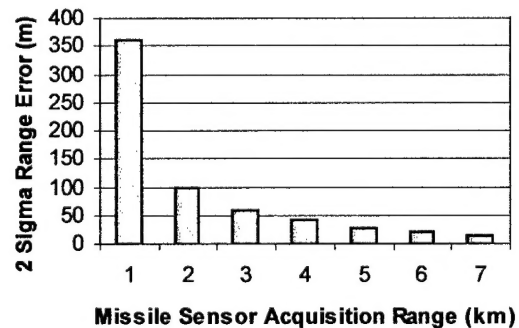


**Figure 5.2-3 8k Stationary Target Range Error versus Seeker Acquisition Range EO Handover.**

show the moving target error growth rate versus acquisition range for an 8-kilometer launch range.
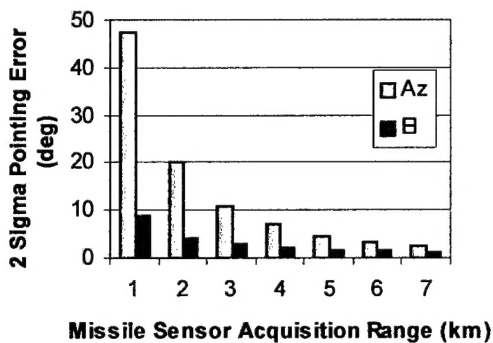


Figure 5.2-4 8k Stationary Target Pointing Errors versus Seeker Acquisition Range EO Handover.

These data show that as the missile closes on the target the angular and range space that the seeker must search grow non-linearly. This is due to two factors. First, for every kilometer that the missile flies prior to acquisition there is approximately 5 seconds of additional time that target rate errors are in effect. Second, as the missile gets closer to the target geometry works against the seeker creating a larger and larger angular space to be searched. This set of conditions places requirements on the missile seeker for acquisition range and field-of-regard (FOR) search rate. Obviously, the greater the missile sensor acquisition range, the smaller the target location error basket.

The large difference in error magnitude between the RF and EO handovers is due primarily to how stationary targeting data is generated in the sensors. The RF sensor model artificially sets line of sight rates to zero if the sensed target velocity falls below a threshold. The effect is a "fixed" target handover with errors only in position. The position errors do not grow with time and the resulting error basket is reasonably small. The EO sensor model retains residual line of sight instability errors that translate into perceived target motion even if the target is truly stationary. This can be easily remedied within the platform and sensor processing. Subsequent studies demonstrated the advantage of zeroing EO sensor rate errors for stationary targets.

Moving targets drive the requirements for long acquisition range and high FOR scan rate even more than stationary targets. The charts provided in Figures 5.2-5 through 5.2-8 below
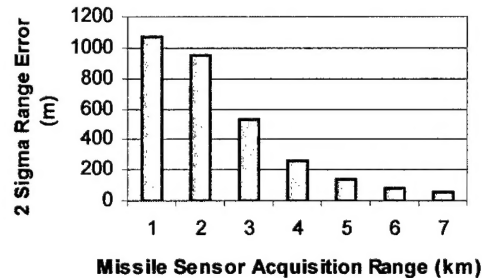


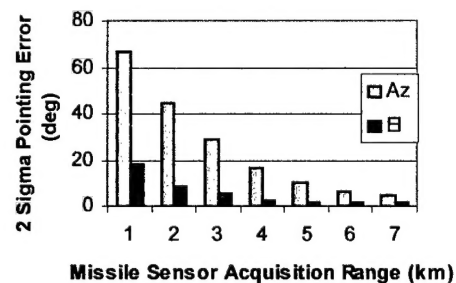Figure 5.2-5 Moving Target Range Error versus Seeker Acquisition Range RF Handover



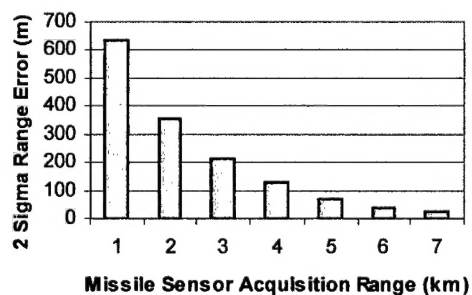Figure 5.2-6 Moving Target Pointing Errors versus Seeker Acquisition Range RF Handover.



Figure 5.2-7 Moving Target Range Error versus Seeker Acquisition Range EO Handover.
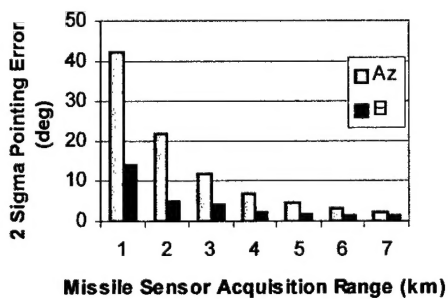
**Figure 5.2-8 Moving Target Pointing Errors
versus Seeker Acquisition Range
EO Handover.**

In general the EO sensor is a more capable targeting sensor; however, for the moving target, the errors in range and pointing are quite large. For moving targets azimuth, elevation, and range rates are passed to the missile and errors in these values grow with time since detection. Artificially fixing the target rate errors is not an option with moving targets as it is with stationary targets, thus the moving target problem presents a more difficult LOAL targeting problem.

## 5.3 Cooperative Engagement Study

Cooperative engagement adds several new variables not considered in the autonomous engagement study. These are:

- Target velocity vector angle to shooter
- Improved/Next Generation Targeting Sensors
- Geometry between spotter and shooter relative to target
- Targeting Data Latency
- Spotter range to target
- Spotter/Shooter heading accuracy
- Spotter/Shooter GPS accuracy
- Missile IMU quality

Sensitivity analysis eliminated spotter/shooter heading accuracy, spotter/shooter GPS accuracy and missile IMU quality as performance drivers. The remaining variables were combined and target location error data calculated for each combination. From these data, best and worst case scenarios were selected for stationary and moving targets. Figure 5.3-1 is a "best case" stationary target engagement. The horizontal

axis is the missile acquisition range in kilometers. The solid target location error curves are for launch ranges of 12, 15 and 18 kilometers. The errors are expressed as the product of the azimuth and elevation pointing error half angles. In this case the targeting sensor has very good error characteristics (similar to a next-generation rotary-wing EO sensor), the spotter is close to the target (5 kilometers) resulting in relatively small rate errors, and the delay between target detection and missile launch is minimal (2 seconds). Also shown on the graph are four missile sensor field of regard search rates. The dashed missile sensor plots begin at the sensor acquisition range and the area searched by the sensor increase as the missile moves toward the target. The four sensors modeled represent four technology candidates for a next generation missile sensor.
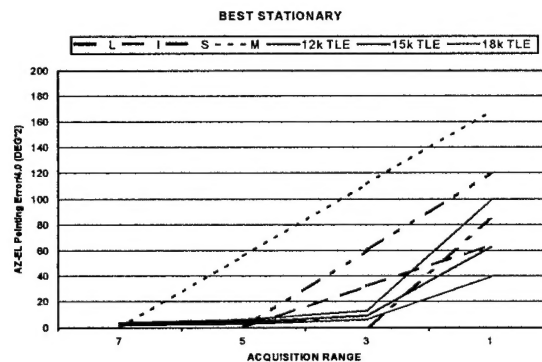


**Figure 5.3-1 Best-Case Stationary Target
Remote LOAL Engagement Errors and FOR
Search Rates.**

Figure 5.3-2 illustrates a "worst case" stationary target LOAL engagement. The spotter sensor errors are larger than in the best case (typical of existing rotary-wing EO sensors), the spotter is separated from the target by a large distance (10 kilometers) resulting in large rate errors, and the delay time between target detection and missile launch is 30 seconds. In the first case, the missile sensors are able to out pace the growth in target errors with the exception of one short range technology at the longest range. Targeting errors are much worse in the second case and the margins for sensor search are reduced.
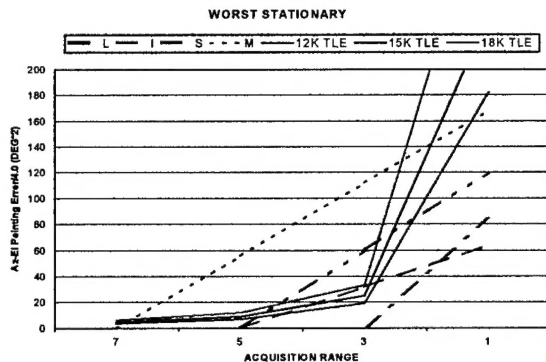
**WORST STATIONARY**



**Figure 5.3-2 Worst-Case Stationary Target Remote LOAL Engagement Errors and FOR Search Rates.**

Again, as in the case of autonomous LOAL, targeting moving targets place a high premium on the missile seeker's acquisition range and FOR scan capability. Figures 5.3-3 and 5.3-4 illustrate the "best case" moving and "worst case" moving target errors and sensor scan capabilities. The ground rules for best and worse case are as above.
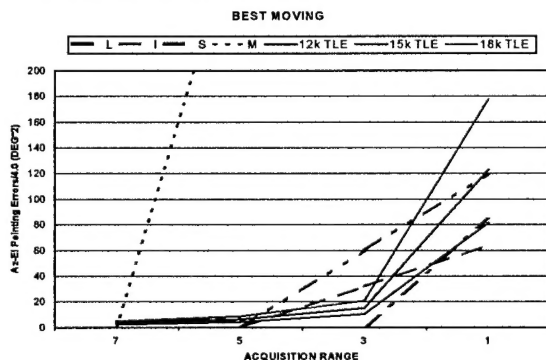
**BEST MOVING**



**Figure 5.3-3 Best-Case Moving Target Remote LOAL Engagement Errors and FOR Search Rates.**

For the moving targets, one of the missile sensors has a higher search and detection rate and this enables it to out pace the error growth even in the worst case. The other sensors cannot keep pace and will be limited in their ability to acquire moving targets at these extended ranges.
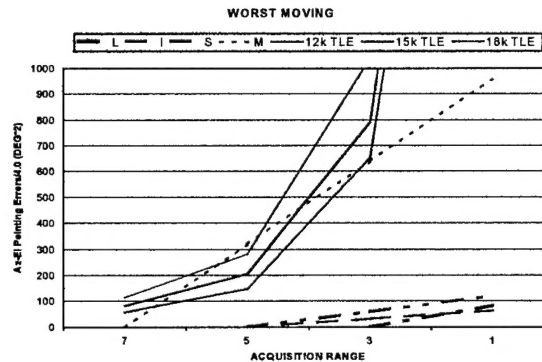
**WORST MOVING**



**Figure 5.3-4 Worst-Case Moving Target Remote LOAL Engagement Errors and FOR Search Rates.**

## 6.0 Conclusions

Next generation tactical missiles will have kinematic range that exceeds the acquisition range of their sensors. LOAL and cooperative targeting have been demonstrated in fielded missile systems and will play a large part in the operational effectiveness of a next generation missile. LOAL targeting stresses the entire weapon system and missile performance is dependent on a variety of factors. For these reasons, missile design must consider the total weapon system and its associated targeting errors. Trade studies have been conducted for both autonomous and cooperative LOAL engagements in an attempt to characterize the systems issues. Conclusions from the trade studies are:

- Platform GPS and INS performance are not drivers.
- Improvements in Missile IMU performance have marginal affect on NLOS targeting scenarios.
- Performance under all conditions is driven by the following:
  - o Initial targeting errors (a function of the detection sensor)
  - o Engagement timeline (a function of detection-launch delay and target range)
  - o Missile sensor acquisition range and search rate
- Cooperative engagement performance is a function of engagement geometry.

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- The requirement to engage moving targets at very long ranges without an in-flight target update to the missile can only be met with a long range missile sensor with robust field of regard search capability.

Improvements in missile LOAL performance can be achieved in many ways. Initial targeting errors can be reduced by improvements to targeting sensors. Increased line of sight stability, measurement accuracy, and targeting algorithms are candidates for improvement. Platform to platform communication infrastructure can be enhanced to reduce targeting data latency. The cost of these improvements and their associated performance benefits must be directly traded against missile sensor cost and performance to achieve an optimal system solution.

Furthermore, missile sensor cost can be further reduced if a means of providing LOAL target cueing in flight is added to the weapon system. This concept is an area of increasing study on the part of both government and industry and presents both benefit and challenges. The primary benefit is the promise of cheaper, short-range, possibly strap-down missile sensors. This benefit must be traded against the difficulties that include:

- Engagements are no longer truly fire-and-forget
- LOBL capability is reduced
- Limited "stand alone" performance for shooter platforms
- Cost for the platforms and the infrastructure to support the new targeting concept
- Increase to missile cost for target update hardware

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Name of Author(s)___Frank St. John  &  William Hester___

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Name of Releasing Official:___Franklin H Miller Jr___

Title:___Manager DoD Security___

Address:___5600 Sand Lk. Rd.___

___Orlando, Fe 32819___

Telephone Number:___407-356-3322___

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